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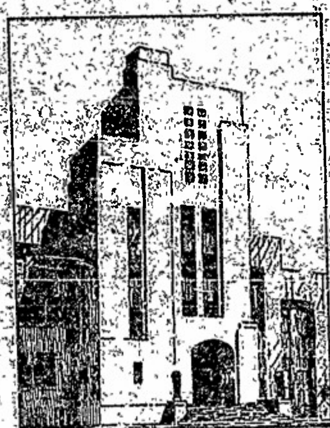
THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

AN ELASTIC-TUBE GAGE FOR MEASURING STATIC AND DYNAMIC PRESSURES

BY E. WENK, JR.



MAY 1948

REPORT 627

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AN ELASTIC-TUBE GAGE FOR MEASURING STATIC AND DYNAMIC PRESSURES

ABSTRACT

An instrument, called the TMB Elastic-Tube Pressure Gage, which consists primarily of an elastic tube and strain-sensitive electrical wire, was developed at the David Taylor Model Basin for measuring a wide range of static and dynamic fluid pressures associated with various types of naval equipment. The design specifications for the gage, novel features of construction of the mechanical and electrical components, and operating characteristics, such as sensitivity, accuracy, and response to rapidly applied pressures, are described. Also discussed are gage-calibration techniques, the use of auxiliary electrical and recording equipment, and operation of the pressure gages in the field under adverse service conditions.

INTRODUCTION

During World War II, the Navy Department expanded and intensified its program of scientific investigations of the operating characteristics of all types of structural assemblies and mechanical devices which comprise a fighting ship. Whenever time permitted, tests were conducted under controlled service or laboratory conditions to determine the performance of items of material and to study the validity of existing design criteria. Frequently it was necessary to determine the magnitude and variation of pressures in fluid media associated with the physical systems under investigation, as, for example, with gun turrets. In the study of gun turrets it was necessary to measure the rapidly generated pressures in the gun barrels and in the recoil and counter-recoil systems of the guns, the fluctuating pressures in hydraulic pumping and variable-speed transmission systems, and the static pressures in air and liquid reservoirs.

With the extreme ranges encountered in such applications, both of the magnitude of pressure and of its rate of variation, it was believed that no unique combination of pressure gage and auxiliary equipment could suffice for all measurements. Nevertheless, it was considered desirable that one type of pressure-sensitive device be suitable under all anticipated test conditions. In 1945 when the need for these instruments arose, no commercial product which would fulfill design specifications was available. Therefore, development of a new device to measure pressure was undertaken by the David Taylor Model Basin.

An instrument, known as the TMB Elastic-Tube Pressure Gage, that combined an elastic tube and strain-sensitive electric wire was found from exhaustive tests to measure pressures accurately under various service conditions, and a number of these instruments were put in operation in July 1945.* These gages were first described briefly in a memorandum (1)** issued for use by employees of the Taylor Model Basin; the instrument was later described in a technical paper (2) for general use. Minor changes have subsequently been introduced to ensure satisfactory operation under the most severe service conditions, and both the original and modified versions of these instruments, which are now in widespread use by various naval research establishments, are described in this report. Sufficient details of construction, calibration, and operating procedures are given so that this report may be used as a service manual for those who are operating instruments manufactured by the Taylor Model Basin as well as a guide for those persons who wish to manufacture their own. Design factors which influence instrument characteristics are discussed in Appendix 1 of this report.

DESIGN AND CONSTRUCTION OF THE PRESSURE GAGE

The design of any pressure gage should necessarily embody all the characteristics required of a precision measuring instrument, for use under known conditions of testing. The explicit design requirements for this particular instrument and the manner in which they were satisfied are discussed in this section of the report.

DESIGN SPECIFICATIONS

Design requirements for this pressure gage were formulated from knowledge of (a) the ranges of pressure and rates of pressure variation to be measured, (b) the actual operating conditions in the field, (c) the characteristics considered necessary in a precision instrument, and (d) the auxiliary amplifying and recording equipment which would be used with the instrument if it incorporated electrical components. These requirements are embodied in a list of requisites which may be considered as specifications:

1. The instrument should emit a linear and undistorted response to static pressures and to cyclic variations as great as 2000 cycles per second or transients which rise in 1/2 millisecond. This requirement implies the need for high natural frequency to ensure fidelity of response to transients.

2. Sensitivity should be sufficient to permit measurement of a wide range of pressures with a single instrument, as for example, 200 to 5000 pounds per square inch; the least count or discrimination should be as low as 1/4 per

* Patent applications have been made for the novel features of this gage that were developed by Lt. R.S. Thatcher, USNR, and Mr. E. Wenk, Jr., of the Taylor Model Basin staff.

** Numbers in parentheses indicate references on page 36.

cent of the maximum value. Peak pressures as low as 50 and as high as 50,000 pounds per square inch should be measurable with this same precision with additional instruments that are based on the same principle.

3. Calibration of the device should be easy and should not require elaborate equipment.

4. Once determined, the instrument calibration should remain independent of age and extremes of meteorological conditions, and should not be disrupted by rough handling.

5. The response of the device should be free of spurious indications of pressure when the gage is exposed to shock and vibrations of moderate intensity, to normal variations of temperature of the ambient atmosphere, and to temperatures of the pressure-transmitting medium as high as 300 degrees Fahrenheit.

6. Superposed instrument errors should be less than 2 per cent of the peak pressure being measured.

7. It should be possible to record pressure at stations remote from the point of instrument installation. Inasmuch as such a device would probably incorporate some electromechanical components, the electrical output should be adaptable for use with existing electronic amplifiers and other equipment which has proved suitable for measuring high-speed phenomena.

8. The device should be relatively simple to manufacture, assemble, install, and operate; it should be compact and durable and have the finished appearance of a commercial product.

It should be noted that these specifications were formulated for use of the device as a measuring instrument, but all the listed characteristics would coincidentally render it useful as a control instrument.

GENERAL PRINCIPLES OF OPERATION

Studies conducted as the first phase of instrument development indicated that a purely mechanical device could not include all the essential prerequisites for satisfactory operation, particularly the requirements of insensitivity to shock, of remote recording, and of accurate response to rapid variations in pressure. The design thus appeared to require a combination of appropriate electrical and mechanical components. Instruments where similar applications of electrical motivation have been used depend on variations in electrical resistance, capacitance, or inductance, which are proportional to the physical quantity being studied. Measurement of the electrical output has then been accomplished with standard indicating or recording equipment. Inasmuch as there had already been developed at the Taylor Model Basin various types of auxiliary equipment for use with strain gages whose electrical resistance varies with mechanical strain, an effort was made to utilize this principle in instruments which were being developed to measure various quantities such as forces, torques, pressures, displacements, and accelerations. By this procedure the required auxiliary equipment could be standardized so as to save development time and resources and to permit a greater flexibility in use where measurements are required of a large number or variety of quantities. Since the resistance-type electrical strain gage, when properly used, possesses all the characteristics required of the electrical pickup of this pressure-measuring instrument, it was adopted as one portion of the device.

The operation of this electrical component is based on the electrical properties of a metallic wire by which proportional changes in resistance are produced by changes in length of the wire (and accompanying changes in cross-sectional area). When such a wire is cemented to an elastic material, it serves as a gage of mechanical strain, since within certain limits of temperature and strain, its resistance changes by an amount that is directly proportional to the change in length of the material on which it is cemented. Thus the wire may be employed in a pressure-measuring device if it is mounted on a mechanical element that is elastically deformed by the application of pressure. Unfortunately, the resistance of the strain wire also changes with variations in temperature and with temperature-induced mechanical strains, which property may produce gross errors in measurement. These extraneous temperature effects may be canceled, however, by the use of properly located tandem strain elements which are connected into an electrical bridge circuit. Provisions for this feature will be discussed later.

For the mechanical component of this pressure-measuring device, two basic structural shapes were investigated - a diaphragm and a tube subjected to internal pressure. In both shapes, fluid pressures produce elastic and thus proportional strains, but with the diaphragm this action occurs only if the center deflection is limited to approximately one-third the thickness. This restriction also places a virtual limit on the maximum strain that can be developed in the diaphragm and thus on the maximum electrical output and sensitivity. Ordinarily this limitation on sensitivity would not be objectionable, but since the design requirements call for the use of but one instrument for measuring a wide range of pressures, a high maximum electrical output and sensitivity were desired.

The tubular shape involved no limitation on strain other than that of the proportional limit of the material which comprises the tube; and since its use offered additional, though less important advantages, it was chosen as the basic mechanical element of the pressure gage.

In principle then, the pressure-measuring instrument, or transducer, was developed as an elastic tube around which is cemented strain-sensitive electric wire. Pressure applied to the inside of the tube produces circumferential strains in the tube, and thus changes in the electrical resistance of the wire. When the strain wires are connected to the auxiliary equipment, electrical signals resulting from the pressure-produced strains are measured or recorded and are convertible to pressure units with an experimentally determined calibration factor.

With the adoption of this basic principle of operation, the design next required the solution of the many electromechanical details that would render the transducer a suitable test instrument.

MECHANICAL DESIGN

The design requirements for the mechanical portion of the pressure instrument, based on the specifications and the selected principle of operation, can be detailed as follows:

1. The dimensions of the pressure-active tube should be a compromise between the requirements for (a) a short length and small diameter for compactness and high natural frequency, (b) a wall thickness sufficient to simplify manufacture, and (c) a combination of geometry and materials of construction such that circumferential strain of approximately 2200 microinches per inch could be developed safely at maximum design pressure.

2. Accommodations must be made for a temperature-compensating strain gage which would be subjected to the same temperature changes and temperature-induced dimensional changes as the gage on the pressure-active tube.

3. Mechanical protection must be assured for the strain gages.

4. A system for venting gases from the tube must be provided, inasmuch as trapped bubbles might distort the response of the instrument to high-frequency transients.

5. Provision must be made for a simple and pressure-tight connection to the pressure source and for simple, effective electrical connections to the auxiliary equipment so that the instruments may be rapidly installed by unskilled personnel.

6. The mechanical design must involve a minimum number of separate pieces which can be manufactured easily.

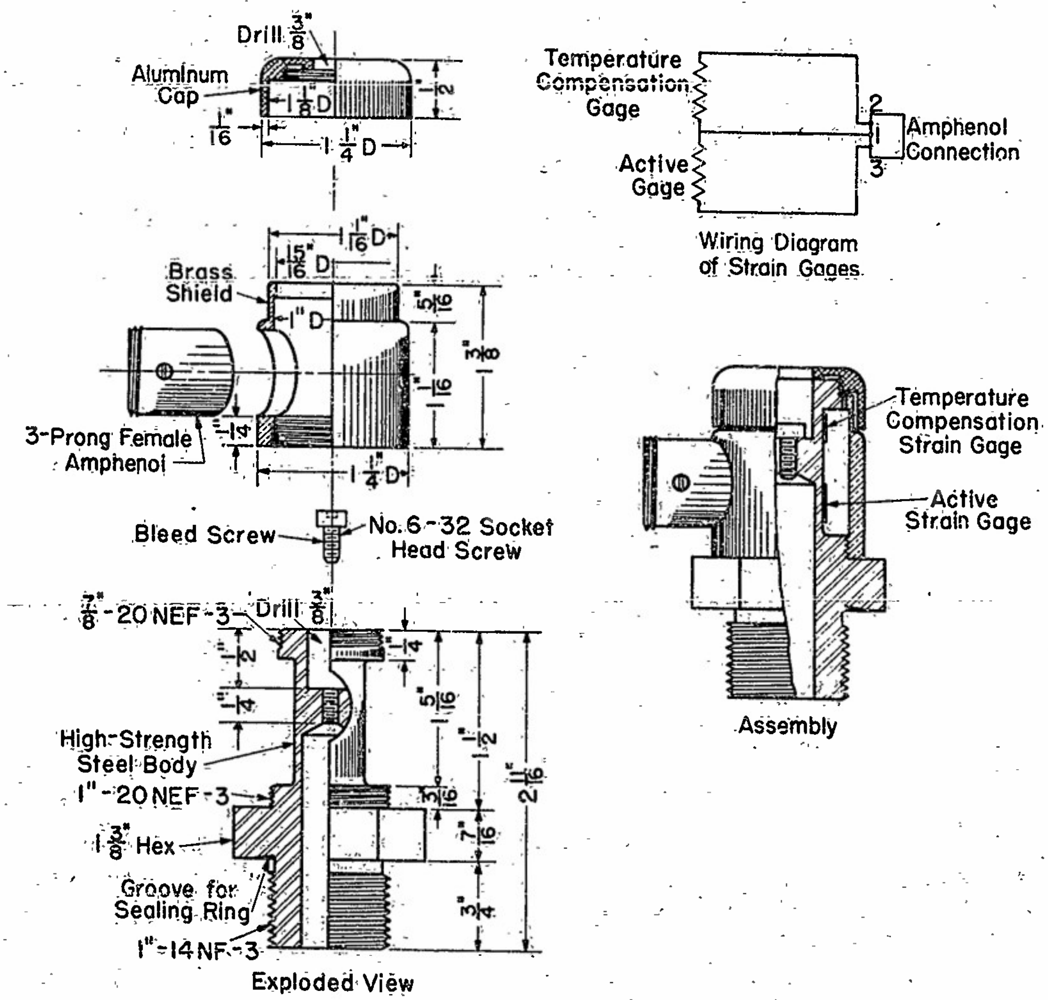

Figure 1 - Schematic Diagram of TMB Elastic-Tube Pressure Gage

This diagram shows details of construction of the original design for instrument types D, E, F, and G. Dimensions of the tube for different pressure ranges are given in Table 1.

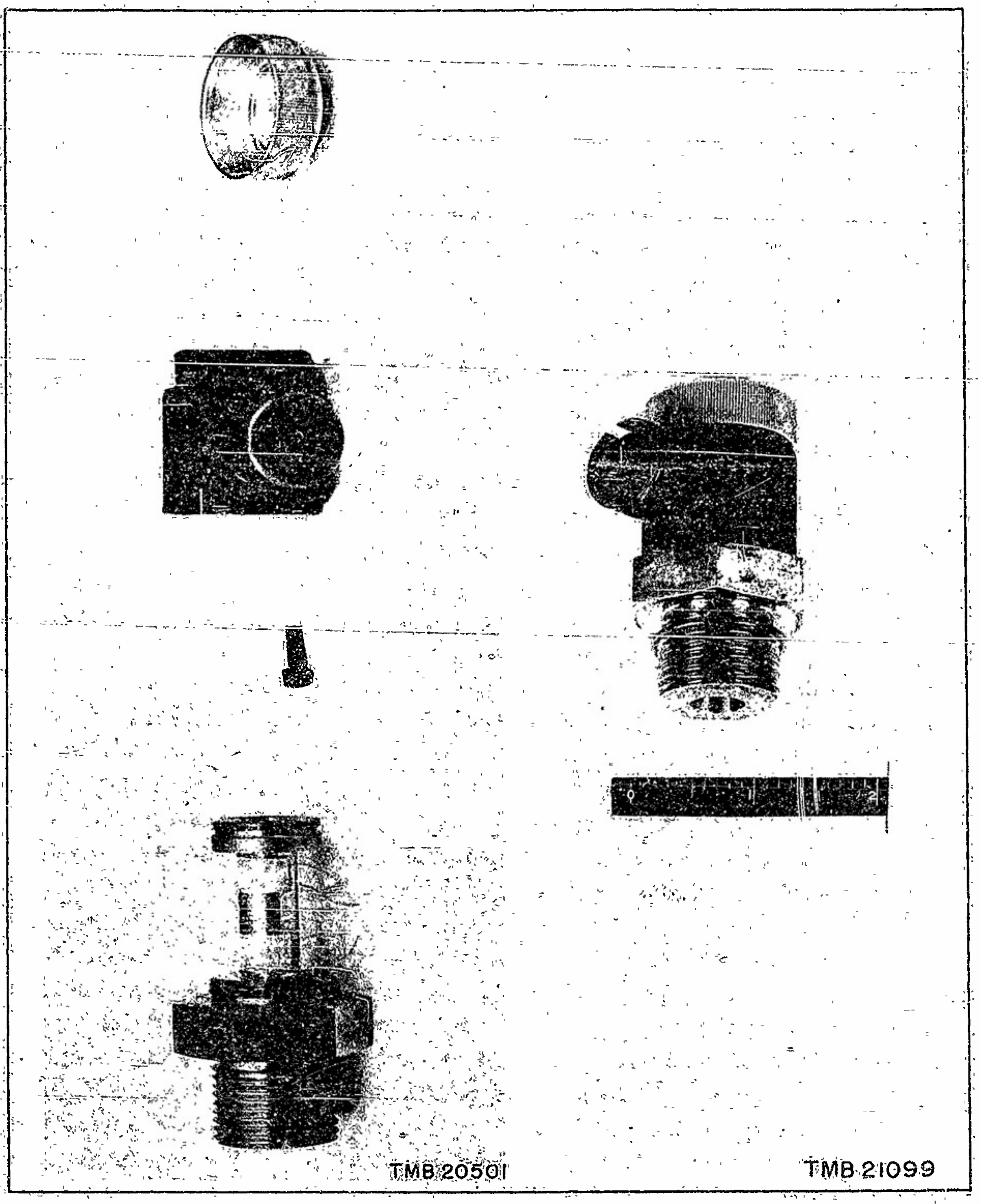

Figure 2 - Components and Assembly of the Original Design of the Pressure Gage

The small number of components and simplicity of manufacture are evident from these photographs. Although this tube is shown equipped with commercial strain gages, hand-wound strain elements are usually employed.

7. The form of the gage should depend on the function and should be as attractive as possible without sacrifice of utility.

After these requirements were formulated, it was also determined that the strain-sensitive wires, though waterproofed, should be still further protected against moisture or oil by a mechanical shield. This latter consideration required modifications to the original mechanical arrangements of the instruments, as will be discussed later.

The mechanical design of the transducer which evolved from the major considerations just listed is shown in Figures 1 and 2. The primary component is a small tube that is separated into two chambers by an integrally formed occlusion. One chamber is attached to the pressure source, while the other is exposed to the atmosphere. The occlusion which blocks the end of the pressure chamber is drilled and tapped for a small screw that can be removed when desired to bleed the active tube.

The tube is also integrally provided with a hexagonal base and threaded shank for attachment to a tapped opening at the pressure source. The hexagonal base is grooved on the shank side to receive an annular copper gasket which serves as a pressure seal. This tubular element is machined of a high-strength alloy steel, Navy specification 49S21, Alloy 2, which has a yield strength of 105,000 pounds per square inch.*

A wall thickness of 0.014 inch was arbitrarily established as the minimum that could be employed in the tube for ease in manufacture, for stiffness, and for insensibility to corrosion effects; the diameter of the tube was then computed from conventional theories of elasticity to produce the desired circumferential strains at the maximum applied pressure. Principal stresses were also computed as a check on the safety of the design. The dimensions of the tube for various pressure ranges are given in Table 1.

As shown in Figure 1, the transducer is provided with a brass shield which surrounds the tube for protection of the strain elements. Attached to this shield is an Amphenol-type electric plug wired to the strain gages to permit making rapid electrical connections to the external amplifying and recording circuits. An aluminum cap which seals the upper end of the shield completes the gage assembly. Clearance is provided between the cap and the shield so that the pressure-active tube when loaded is not restrained from longitudinal elongation, as this restraint could interfere with linear and consistent instrument response.

A large number of transducers which make use of this design have been put into service since since December 1945, and some have been contin-

* Monel or corrosion-resistant steel could be used where corrosive fluids are involved.

TABLE 1

Dimensions and Designations of Elastic-Tube Pressure Gages

Type	Test Pressure psi	Mechanical Design	Dimensions of Tube, inches	
			Outside Diameter	Inside Diameter
D	8000	Original	0.478	0.438
E	5000	Original	0.466	0.438
F	20,000	Original	0.466	0.345
G	1000	Original	0.747	0.718
H	25,000	Revised	0.466	0.345
J	5000	Revised	0.466	0.438

uously exposed to moisture and oil for periods exceeding one year. Examination and recalibration of these instruments revealed only trivial changes in sensitivity, except where a marked drop was discovered in electrical resistance between the strain gages and the metal tube on which they are mounted. This condition was attributed to leakage of moisture over an extended period into the instrument through minute spaces between the electrical plug and its housing and through the crevice between the aluminum cap and the brass shield. Hydraulic fluid in equipment being tested had also entered the shield and had softened the waterproofing compound which protects the strain gages.

Two other minor defects in the mechanical design were also indicated. First, the electrical connection which consists of a modified Amphenol plug had been easily bent when the instruments were installed because of mechanical weakness of the plug housing. Second, maintaining the tolerance of the groove in the hexagonal base for seating the ring-shaped copper gasket was found to be difficult, and this type of seal was found to be ineffective at pressures above 20,000 pounds per square inch.

All these unsatisfactory conditions were corrected by slight modification of design. For pressures under 20,000 pounds per square inch, the original mechanical components of the transducer were revised to those arrangements shown in Figures 3 and 4; and for higher pressures, to those shown in Figures 5 and 6. The tubular element for the new low-range transducer differs from the original element mainly in the provision of integrally machined ridges at the top of the tube to hold a neoprene "O"-ring which seals the gap between the tube and shield. Further, the shield itself is attached to the base of the tubular element with a clamping nut which permits attachment of the shield without the rotation which was necessary to engage threads provided in the

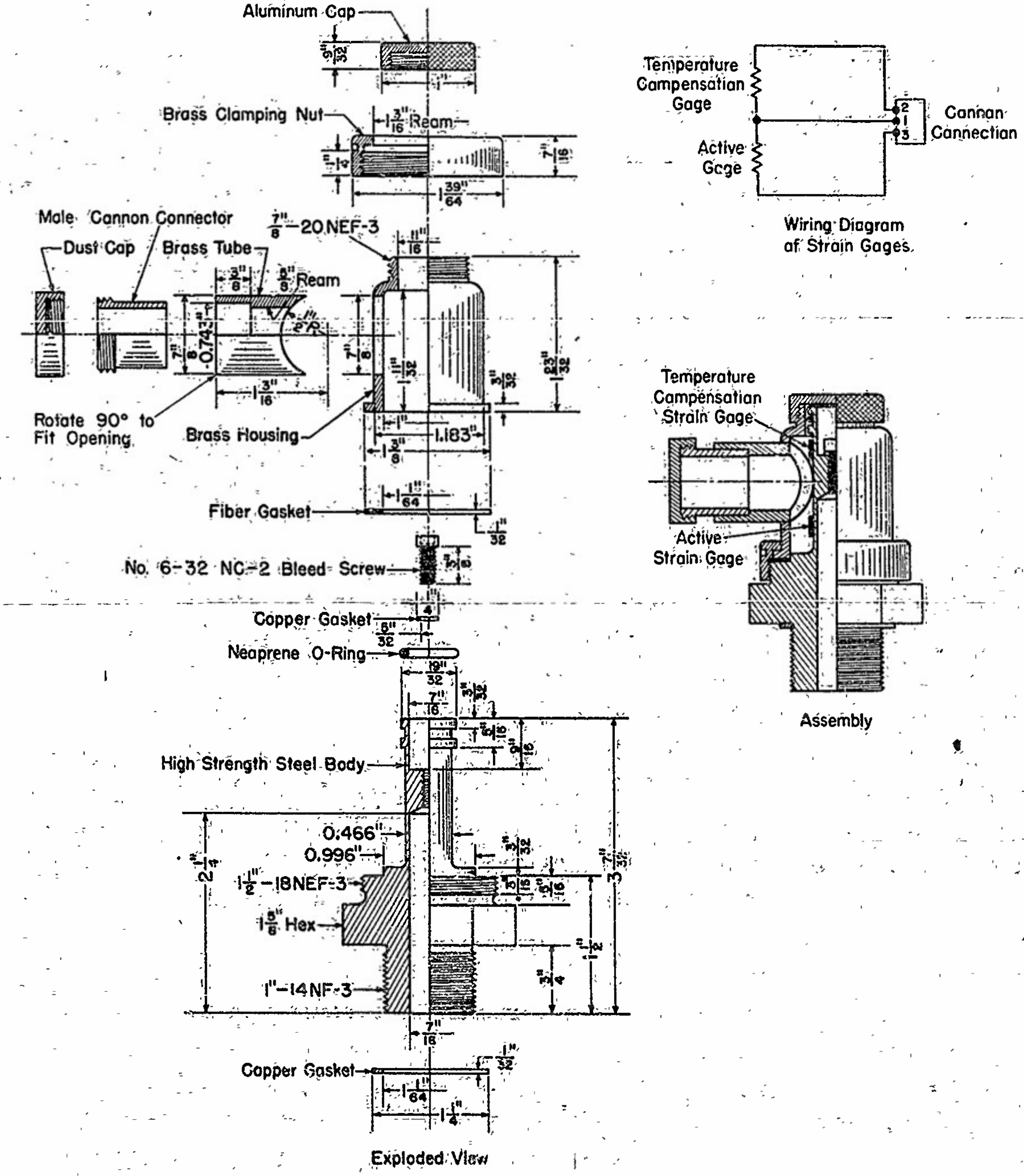

Figure 3 - Schematic Diagram of Revised Elastic-Tube Pressure Gage, Type J

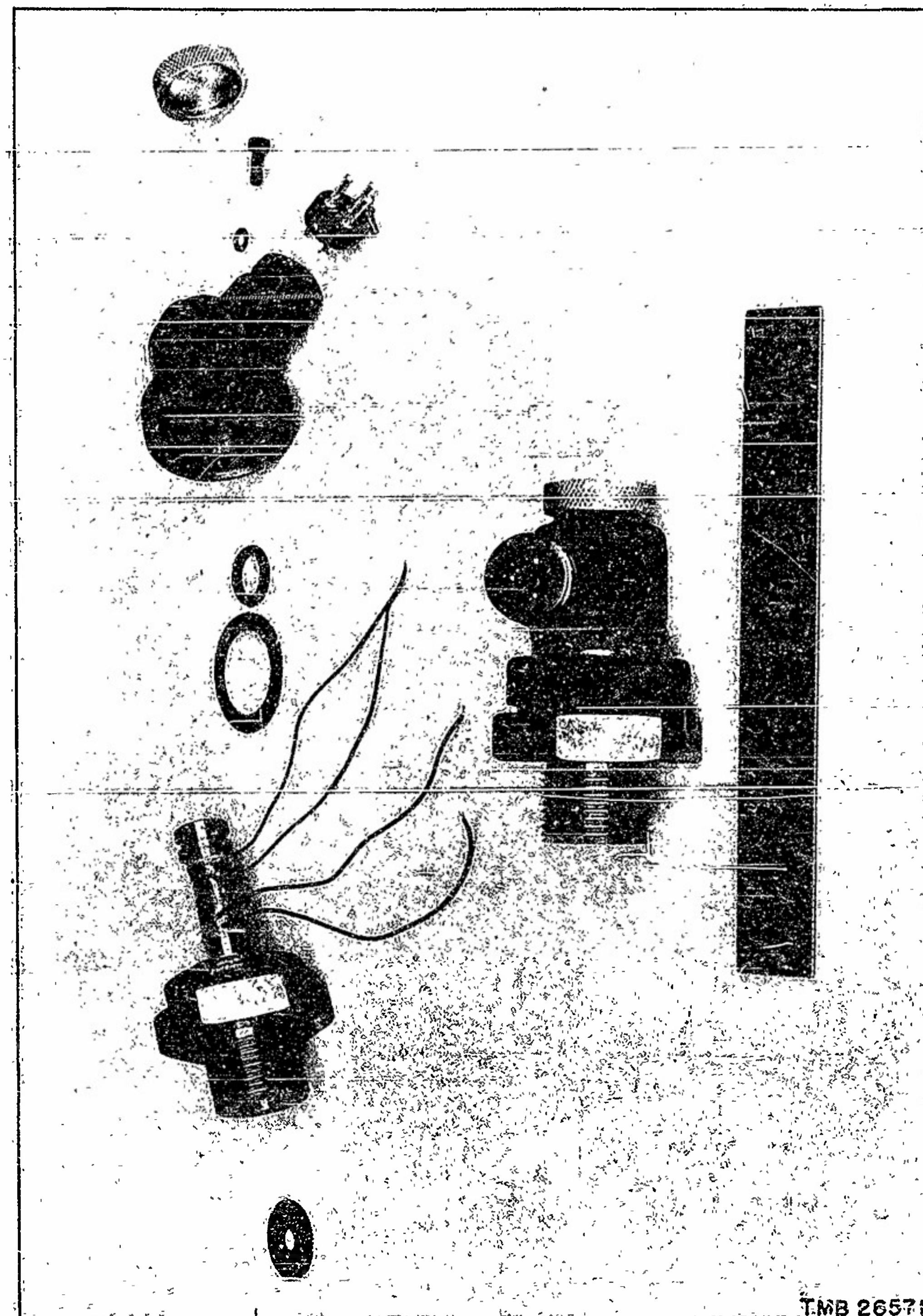

Figure 4 - Components and Assembly of the Revised Elastic-Tube Pressure Gage, Type J

This instrument is a modification of the original design for use at pressures under 10,000 pounds per square inch. The principal modification is in the means of keeping the mechanical shield completely tight against leakage of oil and moisture. Another difference is the use of a Cannon type of electrical plug instead of the Amphenol type.

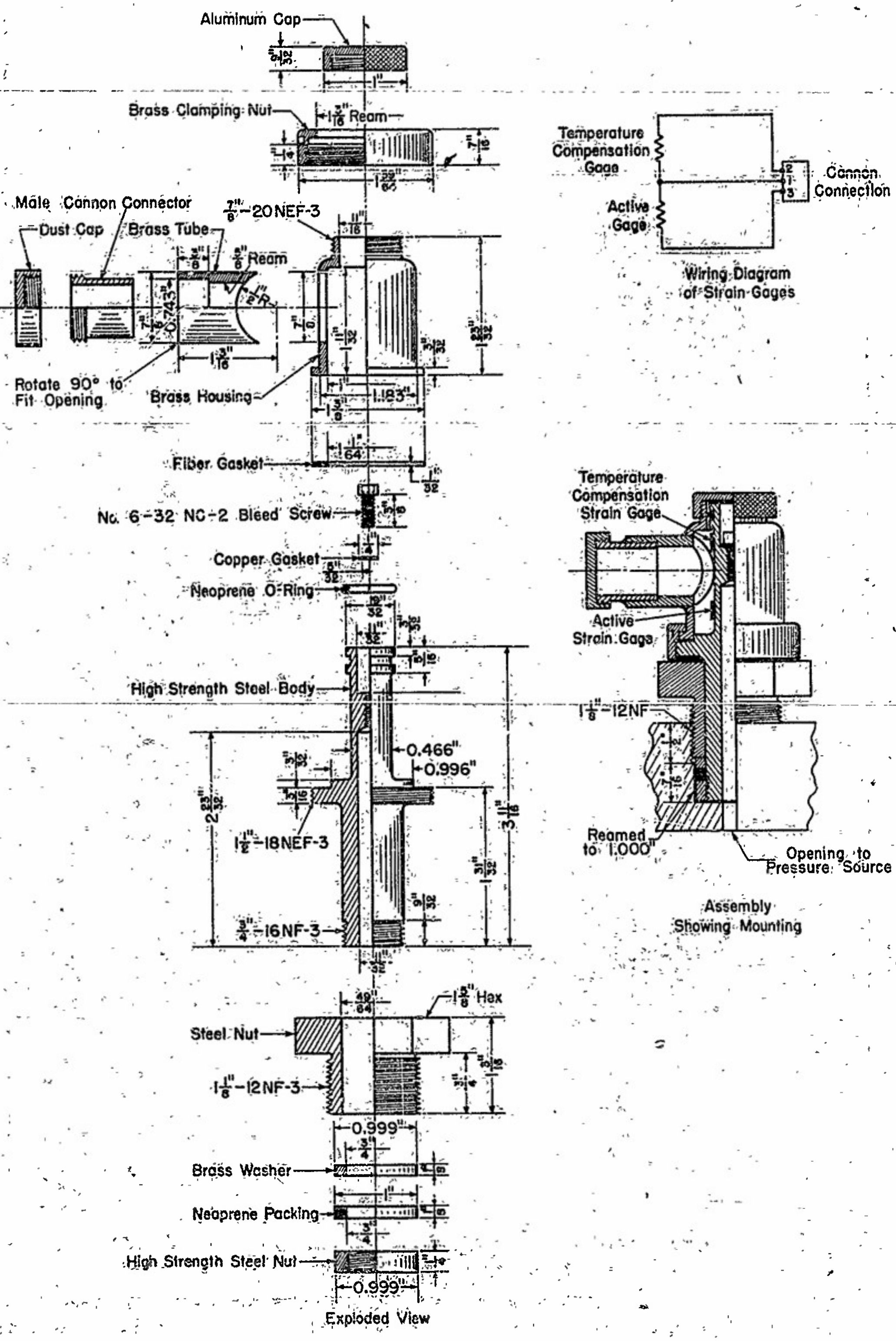

Figure 5 - Schematic Diagram of Revised Elastic-Tube Pressure Gage, Type H

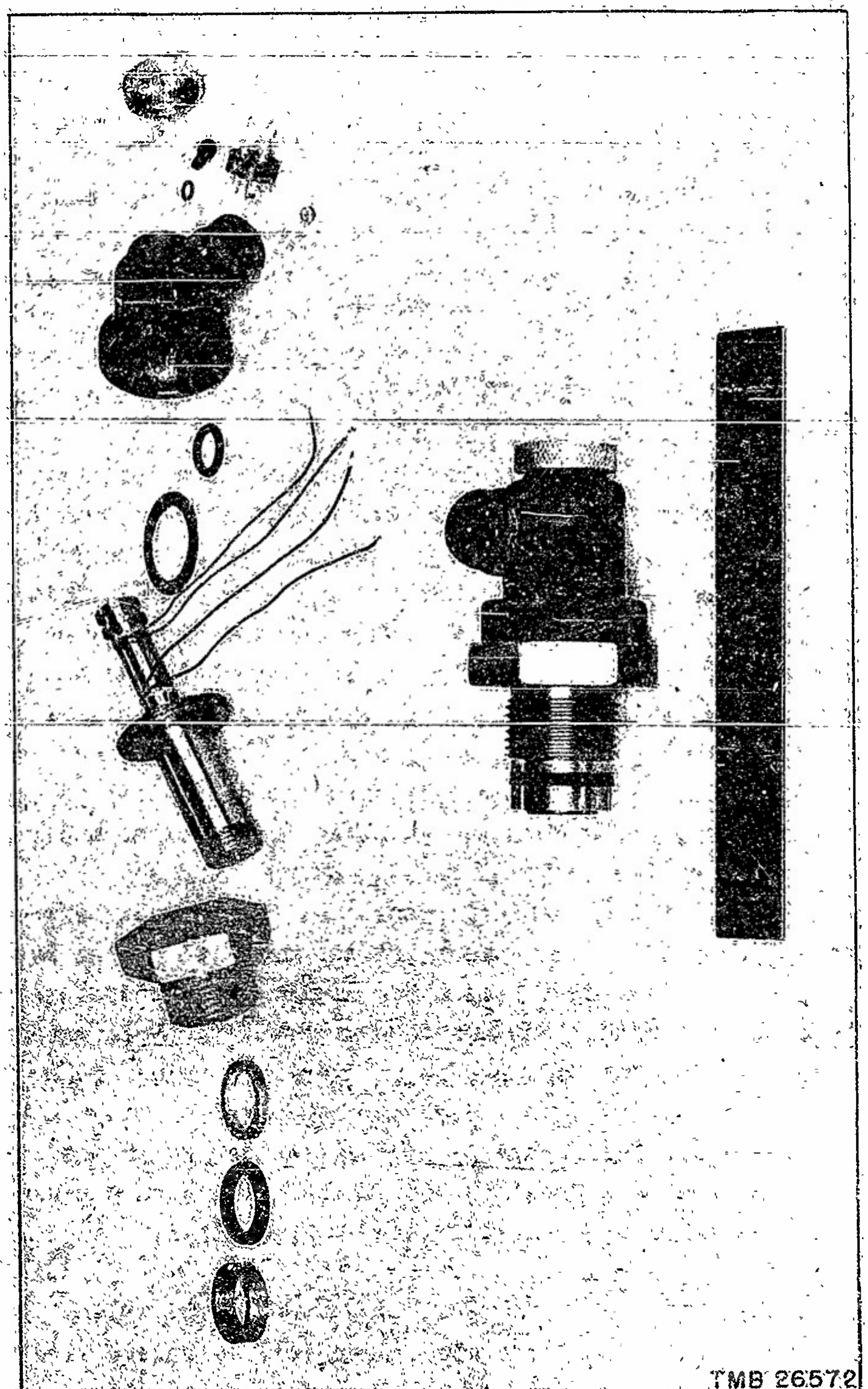

Figure 6 - Components and Assembly of TMB Elastic-Tube Pressure Gage, Type H, for Use at High Pressures

These instruments are similar to the modified design, Type J, except for a pressure seal that is useful in the range of 10,000 to 50,000 pounds per square inch.

original tubular element. The elimination of this rotation facilitates connection of the electrical leads from the strain gages to the plug. Also, in the new instrument a flat annular gasket is provided as the pressure seal, thus eliminating the groove in the hexagonal base. The connection formed by this method has proved to be tight for pressures up to 10,000 pounds per square inch. It should also be noted that the aluminum cap on the new transducer has no opening at its center as did the earlier one, so that the new cap must be removed with the bleed screw when exhausting the instrument of trapped gases.

One further modification is the use of a Cannon type of electrical plug instead of the Amphenol type. This new plug can be equipped with a waterproof dust cap when not in use or with a waterproofed matching plug when making electrical connections.

The design of the transducer for use with pressures from 10,000 to 50,000 pounds per square inch is similar to that for lower pressures except for the means of attaching the instrument to the pressure source. Here the tubular element is provided with a shank on which is loosely fitted a mounting nut, a brass washer, neoprene packing, and a smaller assembly nut. The fitting is designed to match an opening at the pressure source which is reamed to a diameter that exactly matches that of the washer, and which is tapped at its top to match the mounting nut of the instrument. The bottom of this opening should be flat to receive the instrument, and the depth must be such that the assembled transducer bottoms when the mounting nut is tightened. Sealing action occurs by expansion of the neoprene packing between the shank of the tubular element and the wall of the machined opening at the pressure source.

Since most of the instruments of the original design have performed satisfactorily in service, their use under limited conditions has been continued. Where service conditions are severe, however, their shields have been modified to incorporate the Cannon type of electrical plug rather than the Amphenol type.

All gages are designated by a serial number which indicates the type of transducers and the peak pressure, for which the instrument was designed. This system of identification is explained in Appendix 2.

STRAIN-GAGE ELEMENTS

As previously described, strain-sensitive electric wire was mounted on the outside surface of the pressure-active tube to convert mechanical strains to changes in electrical resistance. A variety of hand-wound and commercial gages with different initial resistances have been used; the characteristics of these gages and their operation are discussed in the following.

The basic principle of operation of the strain wire is expressed by the relationship

$$\Delta R = KRe + \rho T$$

where R is the initial resistance of the wire in ohms,

e is the mechanical strain of the material to which the wire is cemented, and in this gage is a direct function of the applied pressure and of change in temperature,

K and ρ are constants that depend on the characteristics of the strain wire,

T is the temperature, and

ΔR is the change in resistance of the wire in ohms.

For various reasons that will be explained in the later discussions, the ΔR of a gage is often expressed in strain units of microinches per inch.

From this expression, it can be seen that a change in resistance of a single strain gage is produced by changes in temperature as well as by mechanical strain, so that gross errors in strain measurement may accompany variations in fluid or ambient temperature. With the pressure transducer, strain gages are installed in pairs, one mounted on the active segment of the tube and the other on the segment exposed to the atmosphere. These two gages are sufficiently close together that the changes in their resistances produced by temperature changes and by temperature-induced dimensional changes are approximately the same. If these gages are connected into adjacent arms of a suitable Wheatstone bridge circuit, the equal changes of resistance do not unbalance the bridge, and no spurious electrical signals will be emitted from the pressure-measuring system as a result of temperature changes. Pressure-produced change in resistance of the strain wire mounted on the active segment will unbalance the bridge and in a properly designed circuit an electrical output will be produced that is almost exactly a linear function of the applied pressure.

Commercial metalectric strain gages were used with the transducers that were first manufactured. Type A-14 gages were used where a gage resistance of 500 ohms was required, and Type A-7 where a resistance of 120 ohms was required. Generally, the instruments with A-14 gages were more stable and accurate than those with A-7 gages. However, both types of commercial gages have since been superseded by strain-sensitive wire that is hand-wound on the tube to the desired resistance. Hand-wound gages require considerably more care in manufacture but are more reliable.

The strain elements are mounted as follows: Commercial-type strain gages are first pre-curved to fit the tube, and then cemented with Duco. After air-drying for 48 hours, the gages are heated with infrared lamps to 130 degrees fahrenheit for 8 hours, and are then waterproofed with a bitumastic compound such as Ozite B, or with neoprene. The process of applying neoprene is explained in detail in Appendix 3. Standard procedures are used in preparing the surface of the tube and in carrying out other details of application.

Single-strand silk-covered enameled Advance wire, 1.5 mil in diameter, is used when the gages are wound on the tube by hand. All wires are pre-cut to the length required to produce the desired strain-gage resistance after assembly.* The wire is then doubled and the end of the loop thus formed is cemented to the tube with a drop of prepared cement.** The tube is then put in the chuck of a hand drill which is held in a vise, and the wire is wound directly on the tube with the axis of the drill inclined just enough to cause each turn of the strain wire to fall next to the preceding turn. To ensure constant tension in the wire, a 2-ounce weight is hung from the free ends by means of a spring-clip with rubber-padded jaws. Before the wire is wound, the tube is coated with cement; after the winding is completed the entire surface is saturated with thinned cement. The short ends of the strain wire are tinned and soldered to flexible leads, and the joint thus formed is insulated from the tube by a thin sheet of nylon or Saran film. The flexible leads are later connected to the output plug. The waterproofing process is identical to that employed with commercial gages, and the compound is applied to keep these electrical leads as rigid as possible. The resistances of the active and the temperature-compensating strain gages should be equal to within $\pm$ 0.5 ohm. When the initial resistance of the gages is 120 ohms, the transducer is immediately adaptable with auxiliary equipment which is designed for use with metalectric gages for the direct measurement of strain, such as the Baldwin Southwark SR-4 Static Strain Indicator and equipment similar to the TMB Type 1A Strain Indicator (3). For some measurements, however, it is necessary to use a conventional d-c Wheatstone bridge feeding either a direct-coupled amplifier or a recorder, and in these cases it is desired to force the electrical output of the transducer system to a maximum. This may be accomplished by using a higher battery voltage for the bridge power supply; but to maintain bridge current as low as possible,† it is necessary to employ strain gages whose resistance is as great as 500 or 1000 ohms. This higher resistance may be attained easily with the hand-wound gage.

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* The resistance of the strain wire changes during assembly because of tension produced by the winding process.

** This cement consists of 25 grams of granulated celluloid No. 2346 dissolved on one pound of ethyl acetate.

† For maximum stability of operation, gage current should be approximately 2 milliamperes. However, only slight difficulty has been experienced with current as great as 20 milliamperes, and even 40 milliamperes for short periods of time where maximum output was required.

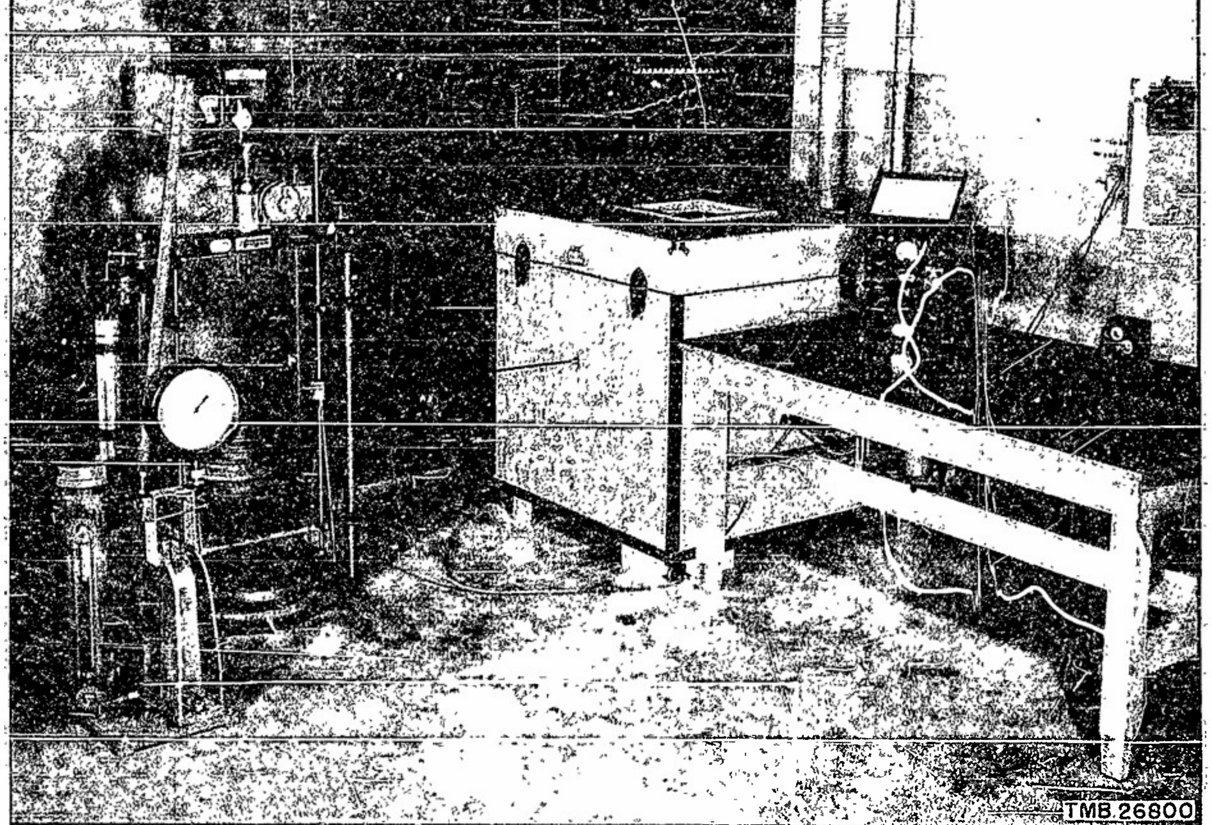

Figure 7 - Photograph Showing Arrangement of Test Apparatus for Calibration of Pressure Gages

Instruments under test are mounted inside the insulated cabinet which can be maintained at any desired temperature between -60 and +200 degrees fahrenheit. Pressure is generated by means of the hand pump located at the far left, increased to 50,000 psi, if desired, with an intensifier, and measured with a dead-weight tester. The tester is equipped with a means of balancing out the initial weight of the cradle so that low pressures can be accurately measured.

Electrical output of the pressure gages is measured with the Baldwin-Southwark Static Strain Indicator shown on the table.

INSTRUMENT CALIBRATION AND OPERATING CHARACTERISTICS

The TMB Elastic-Tube Pressure Gages are statically calibrated at room temperatures with pressures applied by a hand pump and measured with a dead-weight tester which has a precision of 0.1 per cent for pressures of 5000 pounds per square inch or greater. The electrical output is measured with a Baldwin-Southwark SR-4 Strain Indicator* in strain units approximated to the closest 5 microinches per inch. A schematic diagram of the test setup is shown in Figure 7, and a sample calibration chart is given in Figure 8.

* During calibration, the gage-factor control on the Baldwin-Southwark Strain Indicator is set on 2.00. This corresponds to the value for which calibration resistors are designed in the auxiliary equipment described on page 22.

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CALIBRATION OF PRESSURE GAGES

Gage No. EC 5	Maximum Pressure during Calibration 5000 psi	Sensitivity K at 80°F 404 μin/in/1000 psi
Date of Calibration 28 August 1946	Usable Pressure Range 0 - 4000 psi	Sensitivity K at 20°F 404 μin/in/1000 psi
Resistance of SR-4 Gages 500 Ω	Usable Temperature Range 0°F — 140°F	Sensitivity K at 120°F 402 μin/in/1000 psi
Resistance to Ground >500 MΩ	Maximum Zero Shift 15 microin./in.	Calibration by M. E. Duke
SR-4 Gage Factor 2.00	Indicator No. D-58146	Checked by W. Hunter

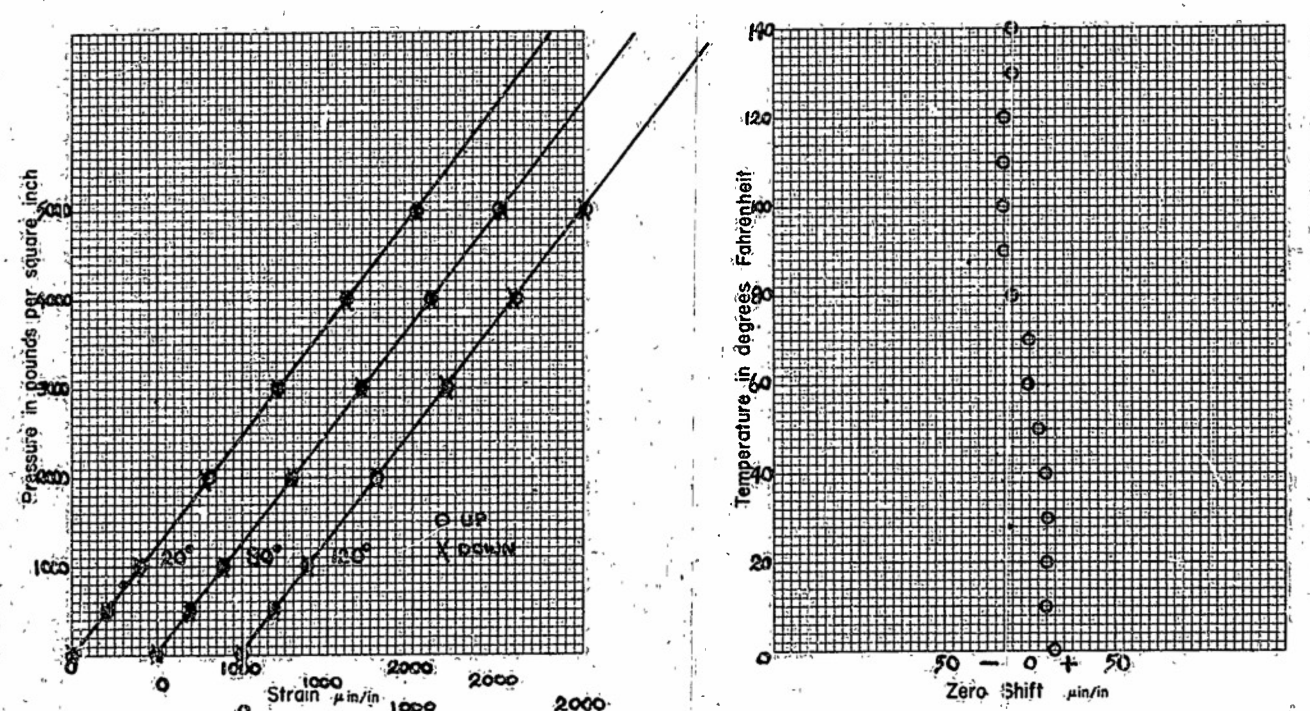


Figure 8 - Sample Calibration Chart of an Elastic-Tube Pressure Gage

The sensitivity of an instrument is expressed in terms of microinches per inch per unit pressure. It is determined from the slope of the line that best fits plotted points of instrument output with both increasing and decreasing pressures. Sensitivity is measured at three different temperatures to check possible errors due to temperature effects. Zero shift is also measured, and if greater than 50 microinches per inch, the instrument is rejected. The results shown here are average, with some instruments showing slightly better and some slightly poorer characteristics.

Each elastic-tube gage is loaded to the rated capacity before the strain wires are applied. After the assembly is completed, pressure is again applied in convenient increments, and observations are plotted concurrently for use in controlling the test as it progresses. This loading is arrested when the instrument output indicates a strain of 2500 microinches per inch. At this point, appreciable deviation from a linear pressure-strain relationship may be detected. Loading is then repeated with observations recorded both with increasing and decreasing pressure; here, however, the peak pressure is limited to that productive of an output of approximately 2000 strain units.

For an instrument to be considered satisfactory, the relationship of applied pressure to the measured electrical output must be linear, with deviations of less than 15 microinches per inch at all pressures. Pressure gages with greater deviations are rejected and fitted with new pickups. The sensitivity factor of each instrument is determined from the straight line that best fits the plotted strain observations and is expressed in microinches per inch per unit of pressure. Slight variations in the sensitivity are to be found in different pressure gages of apparently identical dimensions, but this condition was not considered objectionable.

To determine the extent of variation in sensitivity with different ambient or fluid temperatures, instruments are also calibrated at 20 and 120 degrees fahrenheit; the permissible variation in sensitivity is limited to 2.5 per cent. Creep and zero shift are carefully determined at approximately 10-degree intervals during temperature tests over the range of 0 to 140 degrees fahrenheit; fluctuations in output readings of more than 50 microinches per inch from the reading at room temperature are considered cause for rejection.

For most satisfactory instrument operation, the resistance between the strain gages and the metal tube should exceed 200 megohms. Electrostatic pickup is generally minimized by grounding the instrument and auxiliary equipment at one common point, and by using shielded electrical cable with the shield grounded only at the recording end of the circuit.

AUXILIARY HEAT RADIATORS

The design specifications require that the instrument be useable with temperatures of the pressure medium as high as 300 degrees fahrenheit. This is far higher than the maximum temperature at which satisfactory performance can be expected because, at temperatures as low as 150 degrees, the cement which bonds the strain gage to the tube softens and loses the adhesive properties required for proper operation of the strain-wire component.

To permit use of the pressure gage at high temperatures, an auxiliary radiator has been devised which reduces temperatures of the pressure medium as

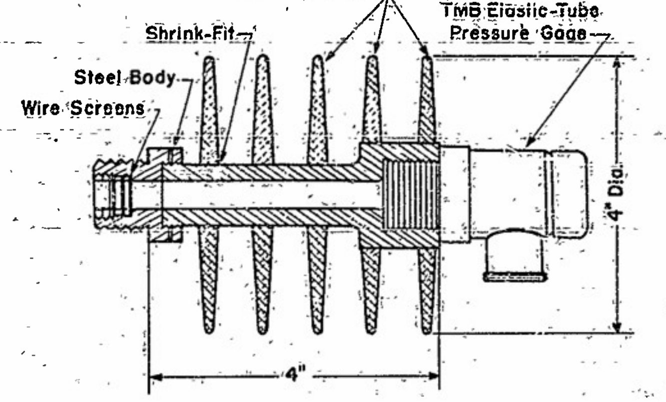


Figure 9 - Convection Radiator for Use with Elastic-Tube Pressure Gage

The pressure gages are usable only if the temperature of the fluid being studied is less than 140 degrees fahrenheit. For liquids at temperatures up to 300 degrees fahrenheit, this radiator can be used to reduce the temperature at the instrument to a satisfactory value. The radiator should be mounted horizontally for most efficient heat transfer.

high as 300 degrees to 140 degrees at the instrument itself. The radiator shown in Figures 9 and 10 is of a convection type to obviate the use of a liquid coolant. It consists simply of a short length of pipe which is equipped with aluminum fins shrunk into place. In use, the pressure gage is connected to the radiator, and the radiator is attached to the pressure source. Care must be taken to mount the radiator in a horizontal position to take full advantage of heat transfer by convection. Wire screens can be provided at the mouth of the radiator to reduce the circulation of the pressure liquid due to internal convection. It should be noted that the radiator has sufficient rigidity so that it expands only slightly when under pressure and thus does not distort pressure pulses transmitted to the instrument itself. Where this instrument is to be used to measure the pressures in hot gases, the radiator and pressure gage must be inclined downward and filled with a pressure-transmitting liquid having a high boiling point.

AUXILIARY ELECTRICAL AND RECORDING EQUIPMENT

Many varieties of electrical, electronic, and recording equipment can be used with the elastic-tube pressure gage to measure the electrical output. For the measurement of static pressures, the transducer can be used with the commercial SR-4 Strain Indicator employed during calibration. This arrangement is shown in Figures 11 and 12. The sensitivity is sufficient so that a single instrument can be used for measuring pressures as low as 200 pounds per square inch, and as high as 5000 pounds per square inch, with a discrimination

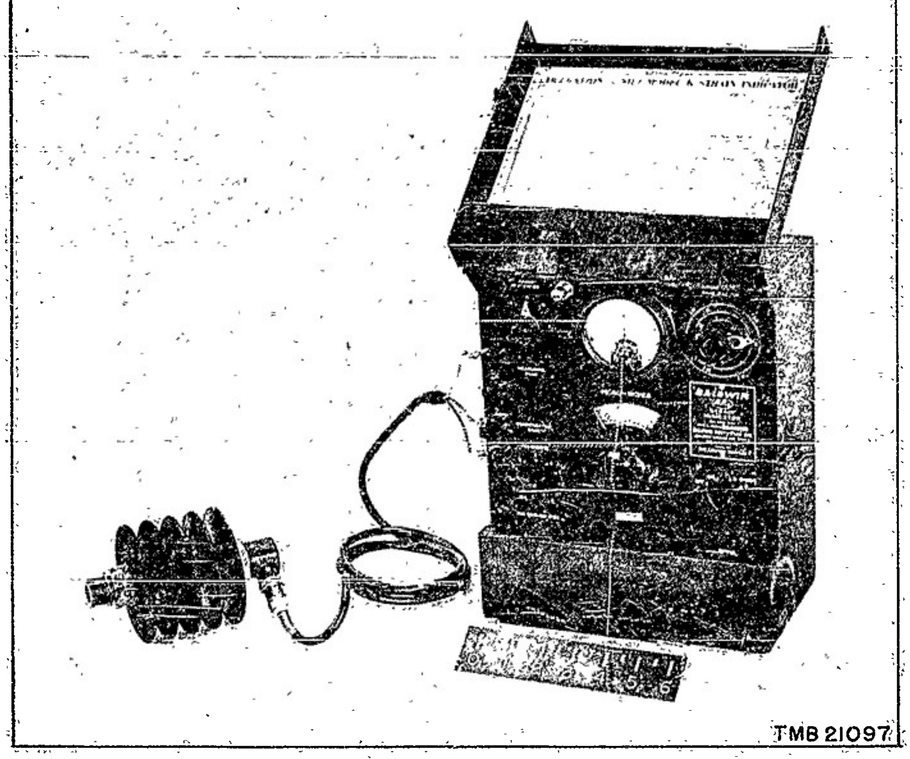
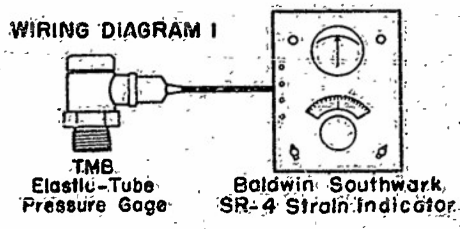


Figure 10 - Original Design of TMB Elastic-Tube Pressure Gage with Auxiliary Heat Radiator and with Strain Indicator Employed for Calibration and Measurement of Static Pressures

of 2.5 microinches per inch, representing approximately 5 pounds per square inch, and an error of 10 microinches per inch or 20 psi at any given pressure. Zero shift should be negligible except for small shifts due to uncompensated temperature effects, and a correction taken from the calibration chart may be applied to reduce this type of error to a minimum. If a particular pressure gage is employed with the same strain indicator that was used during calibration, errors in measurement will be held to a minimum; the characteristics of commercial strain indicators occasionally vary as much as 4 per cent with low strains, so that the use of an indicator different from the one used for calibration may introduce an error as great as 4 per cent.

This same arrangement of instruments can be employed to measure slowly fluctuating pressures provided the peak pressures can be followed by manually maintaining the strain indicator in constant balance.

For high-frequency variations in pressure, which may be either alternating, pulsating, or transient, several different arrangements of auxiliary



Wiring Diagram	Usable Frequency Range CPS	Resistance of Strain Gages Ohms	Least Count in Per Cent of Full-Scale Pressure
1	Static to 2	60 to 500	0.1
2	Static to 60	500 to 1000	1.0
3	Static to 180	120	1.0
4	0 to 500	500	2.0
5	10 to 3000	500	2.0

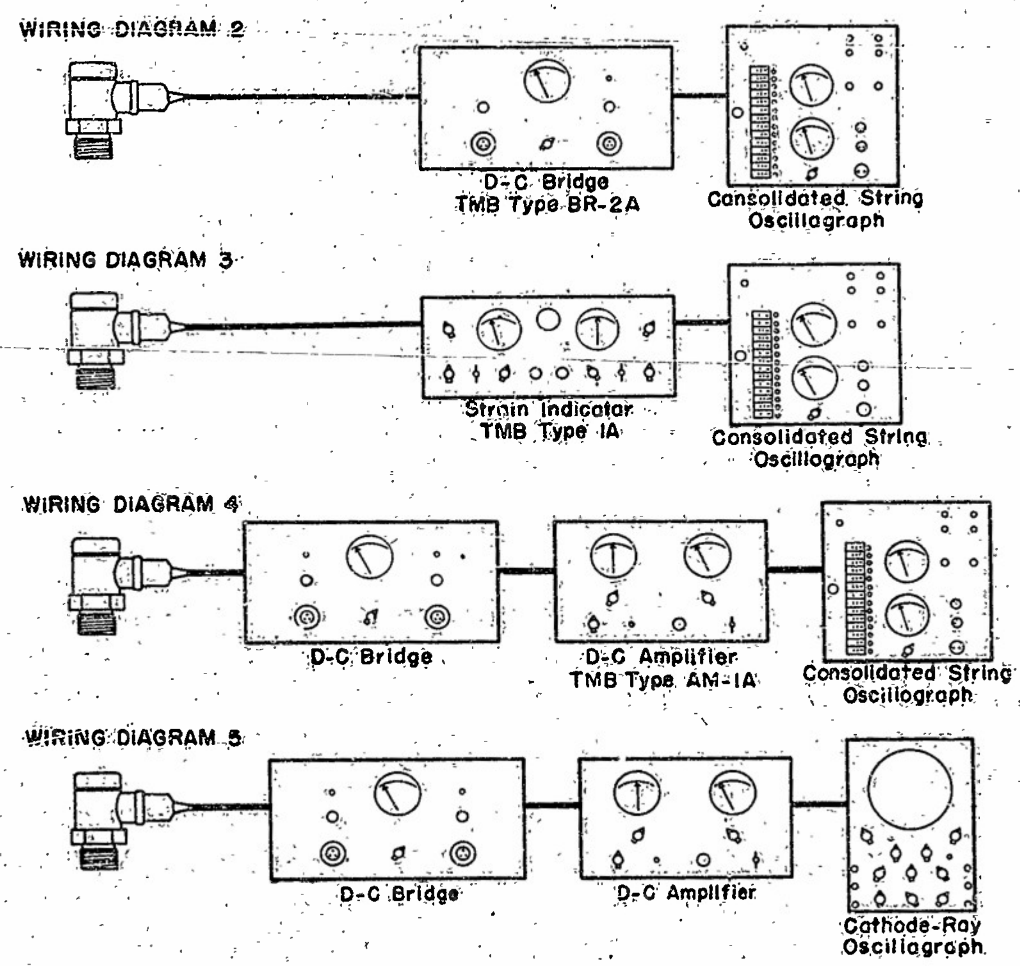


Figure 11 - Schematic Wiring Diagram of Auxiliary Electrical Equipment for Use with TMB Elastic-Tube Pressure Gage

The installation is selected according to the frequency of variation in pressure being measured. Not shown in this diagram are three other arrangements of auxiliary equipment. The pressure gage may be used with a TMB Type 4A strain indicator with a Brush-type ink recording oscillograph for frequencies of 0 to 40 CPS; with a TMB Type 5A strain indicator with string oscillograph for frequencies of 0 to 800 CPS; and with a DC bridge and NOL-type 6 trace cathode ray recorder for frequencies of 0 to 3000 CPS.

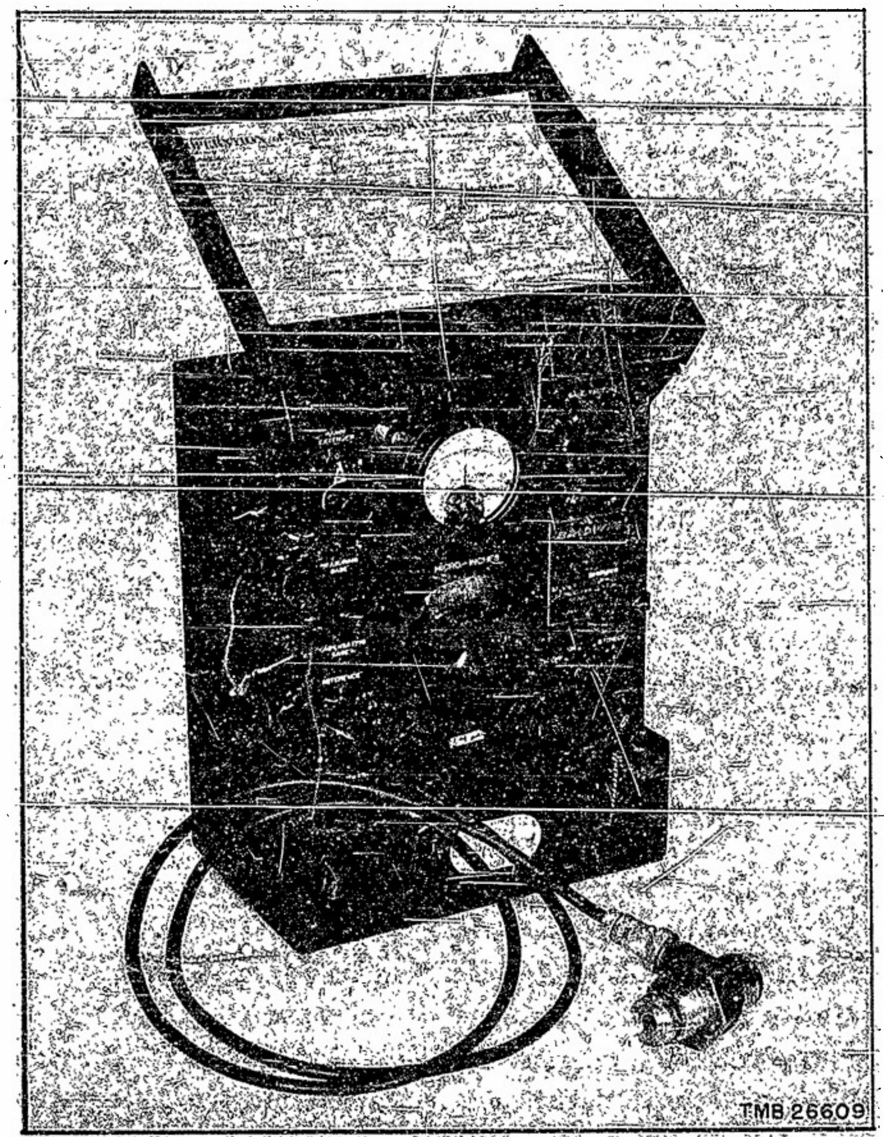


Figure 12 - Test Equipment Required to Measure Static Pressures

The compactness and portability of equipment have proved advantageous for field testing. The length of cable between pressure gage and indicator may be as great as 300 feet, although some increase in least count of measurement occurs with the greater lengths. The strain indicator contains batteries for portability, but should be used with larger capacity batteries when it is permanently installed.

equipment have been found useful. These are listed and shown schematically in Figures 11 through 15 for the entire usable frequency spectrum of the transducer.

For frequencies of pressure variation less than 60 cycles per second, the output of the pressure gage may be fed directly into a d-c Wheatstone bridge and thence to a conventional string oscillograph that contains sensitive

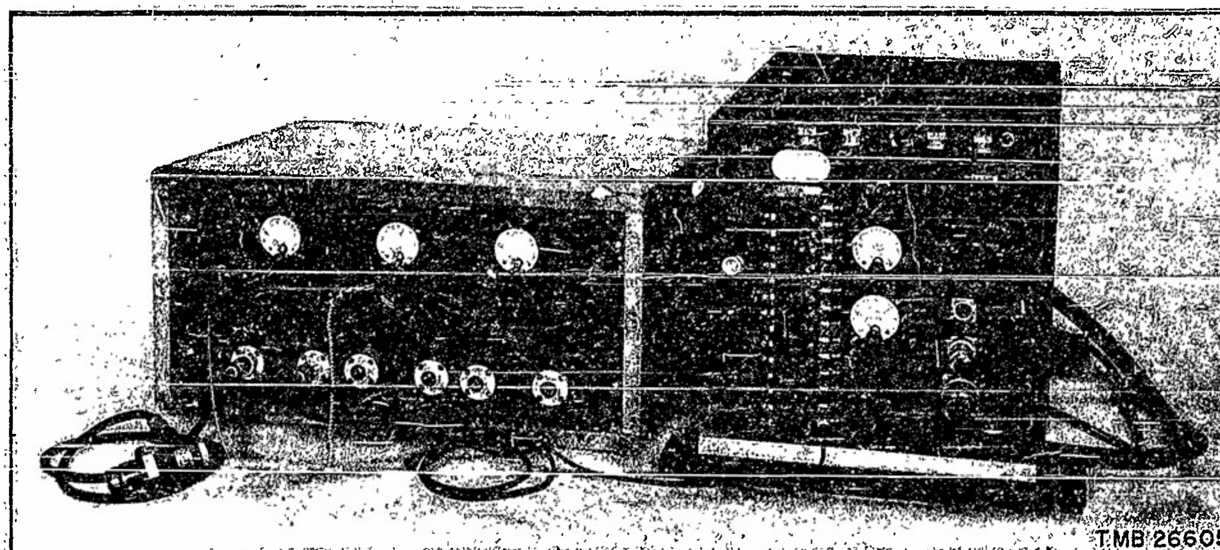


Figure 13 - Test Equipment Useful for Measurement of Pressure Variations up to 60 Cycles Per Second

The elastic-tube pressure gage shown is a Type H gage. The d-c Wheatstone bridge unit is a TMB Type BR-1A and contains three channels, each with balancing and calibration controls. Bridge current may be boosted for short intervals when extraordinarily high gain is desired.

The recording unit is a Consolidated 14-channel string oscillograph equipped with galvanometers giving 1-inch signal per 30 microamperes of driving current.

galvanometer elements. Where frequencies up to 500 cycles per second are involved, galvanometers which possess higher natural frequency but less sensitivity must be employed, and these in turn necessitate greater driving current. A d-c amplifier must then be employed to increase the output of the bridge. This equipment, which has a linear response to signals of frequencies as great as 5000 cycles per second, nevertheless has objectionably low gain and certain instabilities inherent in d-c amplifiers.

For intermediate frequencies, an alternate type of amplifying system has been designed and is identified as the TMB Type 1A Strain Indicator. It utilizes a 2200-cycle dynamic bridge and amplifier with such extreme sensitivity that, when only one instrument is used, pressures as low as 200 pounds per square inch may be measured with the same percentage accuracy as pressures of 5000 pounds per square inch. The stability of the system is excellent; experience has indicated that after the equipment reaches a uniform temperature and with the system at constant pressure, a balance can be maintained indefinitely.

For the measurement of pressures at frequencies higher than 500 cycles, where resolution of the signal is required for both the low- and high-frequency components, the d-c amplifier with dual recording by a cathode-ray oscillograph and a string oscillograph, or an amplifying and recording unit similar to the NOL-type 6 trace cathode ray recorder may be employed.

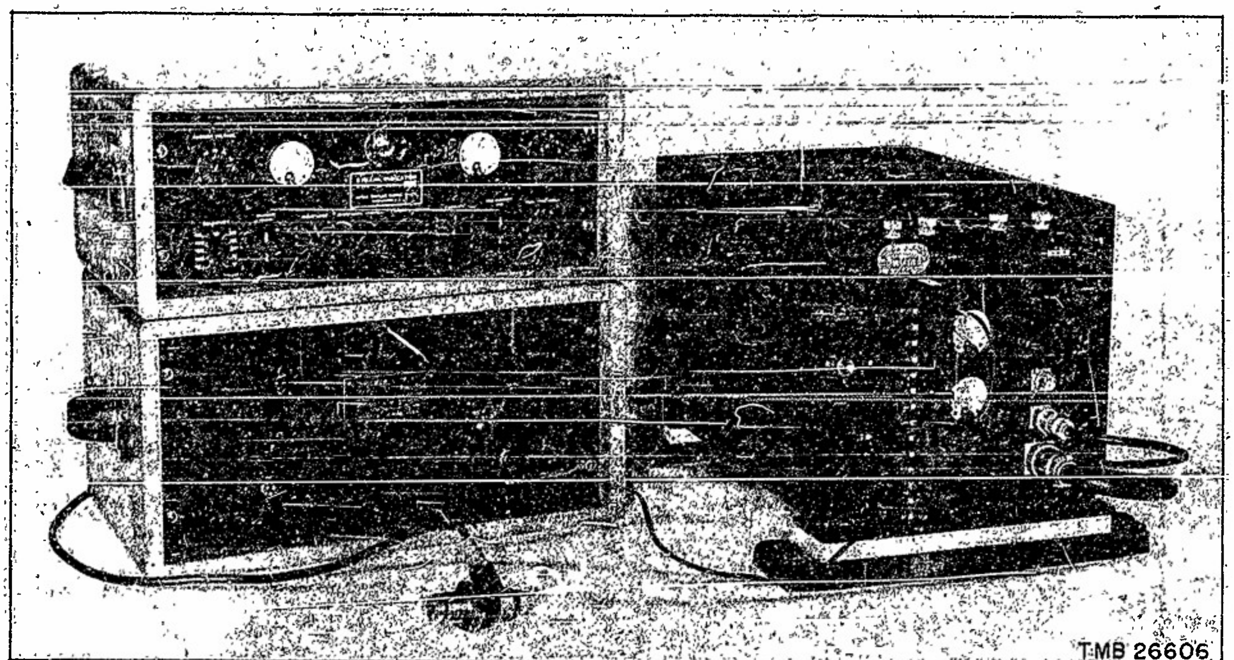


Figure 14 - High-Gain Test Equipment for Measuring a Wide Range of Pressures with a Single Pressure Gage

The pressure gage is shown with a TMB Type 1-A Strain Indicator which incorporates such high-gain amplification that peak pressures from 500 to 20,000 pounds per square inch are measureable with the same test instruments. It is useful for frequencies of pressure variation up to 180 cycles per second with string oscillograph recording. The galvanometer should have a resistance of 12 ohms and responses of 1 inch per 4 mils of driving current, with a natural frequency greater than 1200 CPS.

When the transducer is used with any auxiliary electrical equipment other than the static-strain indicator, some means is required for calibrating the entire measuring system. One method is to calculate the electrical output per unit pressure input from information regarding gain of the amplifiers and sensitivity of the transducer and the galvanometers; however, this procedure is lengthy and requires many subsidiary tests of auxiliary equipment. Another method of calibration is to impress on the test instrument a known pressure during which the electrical response of the system is measured. Inasmuch as the characteristics of the amplifiers are not strictly constant, however, the desired accuracy of measurement could be obtained only if this calibration were performed immediately prior to a test; and for field testing, such a procedure is objectionable.

A more satisfactory scheme, however, has been incorporated in all types of electrical equipment developed at the Taylor Model Basin for use with the Elastic-Tube Pressure Gage. It consists of introducing a small known resistance in series with the active strain element of the transducer so as to unbalance the auxiliary bridge circuit by a known amount. If the value of the

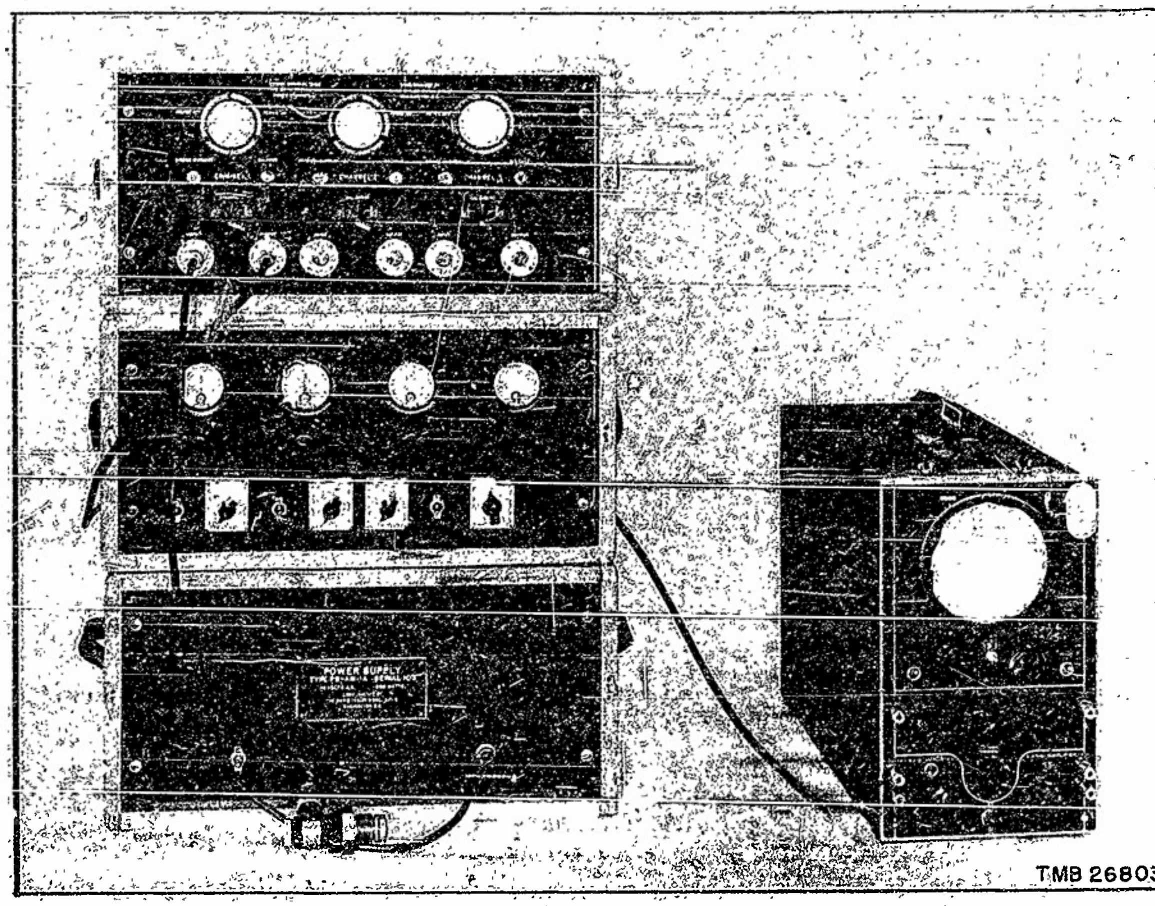


Figure 15 - Test Equipment Used to Measure High-Frequency Variations in Pressure

The pressure gage is connected to a d-c Wheatstone bridge, the electrical output of which is increased with a direct-coupled amplifier. The equipment shown contains three identical channels; it has a useful response up to 5000 cycles per second. The output of the system may be connected to a conventional cathode-ray oscillograph, and the record photographed. For frequencies up to 500 cycles per second, a string oscillograph should be used; both systems of recording may be employed simultaneously to discriminate both low- and high-frequency components.

resistance is accurately known, and if the sensitivity factors of the pressure gage and resistance of the strain elements are determined, the output step pulse produced by switching the series resistor into the circuit represents a specific pressure and serves as an artificial calibration.

The change in resistance required is, of course, small; and to avoid difficulties with switch contacts, a 2-ohm precision resistor is permanently connected in series with the strain gages in both bridge arms and is shunted with a second, larger resistor when the change in resistance is desired.

RESULTS OF FIELD TESTS

Elastic-tube pressure gages have been used in both field and laboratory tests for a period of approximately three years. During this time, instruments were unavoidably exposed to saturated atmospheres, to oil baths, to rough handling, and to shock accompanying gunfire; and with the exception of the minor difficulties mentioned earlier, that were corrected by changes in mechanical design, the instrument characteristics were in no way adversely affected and the response has been free of spurious pressure indications. Some instruments recalibrated after one year of use indicated shifts in sensitivity of less than one per cent. Zero shift was never found to be excessive, and, in fact, the highest degree of stability has always been realized. It is nevertheless good practice to recalibrate the instruments every six months. Non-linear calibration or low resistance to ground require application of new strain gages.*

Instruments have been installed by unskilled workmen without difficulty and have been used by both trained and untrained technicians in this and other naval establishments. Successful applications include the measurement of hydraulic pressures in training and elevating buffers on turrets, in recoil and counterrecoil cylinders of guns, in hydraulic piping, hydraulic motors, and variable-speed transmissions, in Kingsbury hydraulic-type thrust bearings, and of gas pressures in exhaust systems, in gun barrels, and in explosion chambers.

Recording of pressures at distances as great as 250 feet from the instrument has been accomplished with ease.

The feature of bleeding the gage has been found invaluable, because tests to determine effects of entrapped air have shown that with dynamic loading even small bubbles produce gross distortions in the pressure-time relationships and in the magnitude of recorded pressures.

Tests have been conducted to compare this gage with other types, in particular a piezoelectric crystal gage and a mechanical engine indicator. Records were taken simultaneously, as shown in Figures 16 and 17, during the stroke of a hydraulic buffer. The pressure pulse indicated frequencies as high as 700 cycles per second. Agreement of the crystal and elastic-tube gage readings is very close both in magnitude and in time-history; the mechanical indicator overshot slightly and had a distorted response.

The natural frequencies of the Types E, F, and H gages have been measured, and were found to be 1200, 1800, and 1500 cycles per second respectively, when resonating as air-filled organ pipes. When filled with liquids, these frequencies will be raised appreciably. Frequencies when vibrating as

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* Instruments overloaded by more than 20 per cent are generally impaired so that new strain elements will not improve performance; see footnote, page 31.

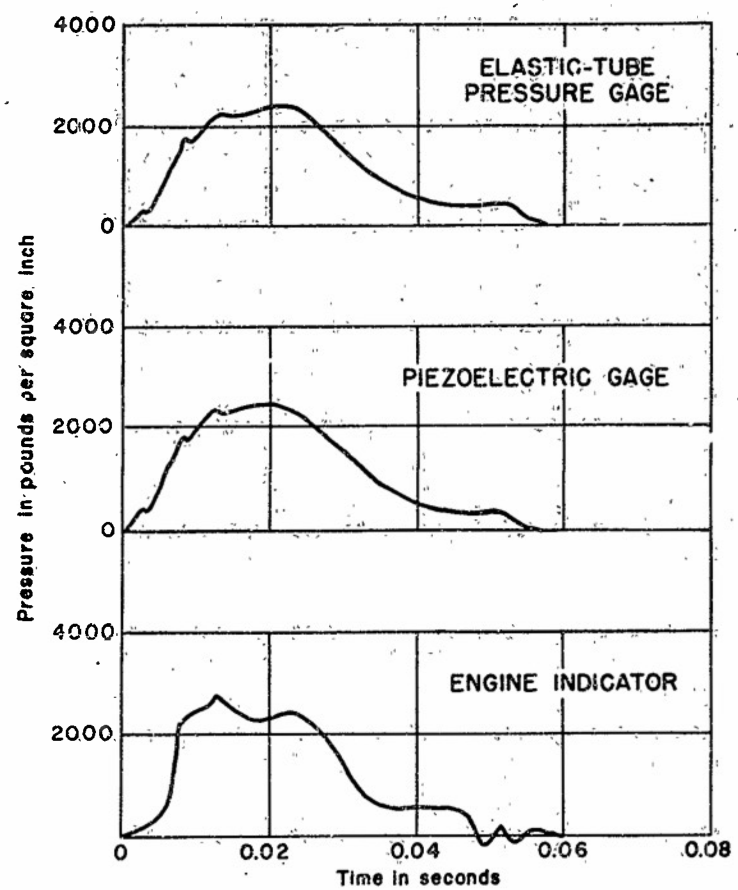

Figure 16 - Comparison of Pressure-Time Relationships Recorded with Different Gages During a Stroke of a Hydraulic Buffer

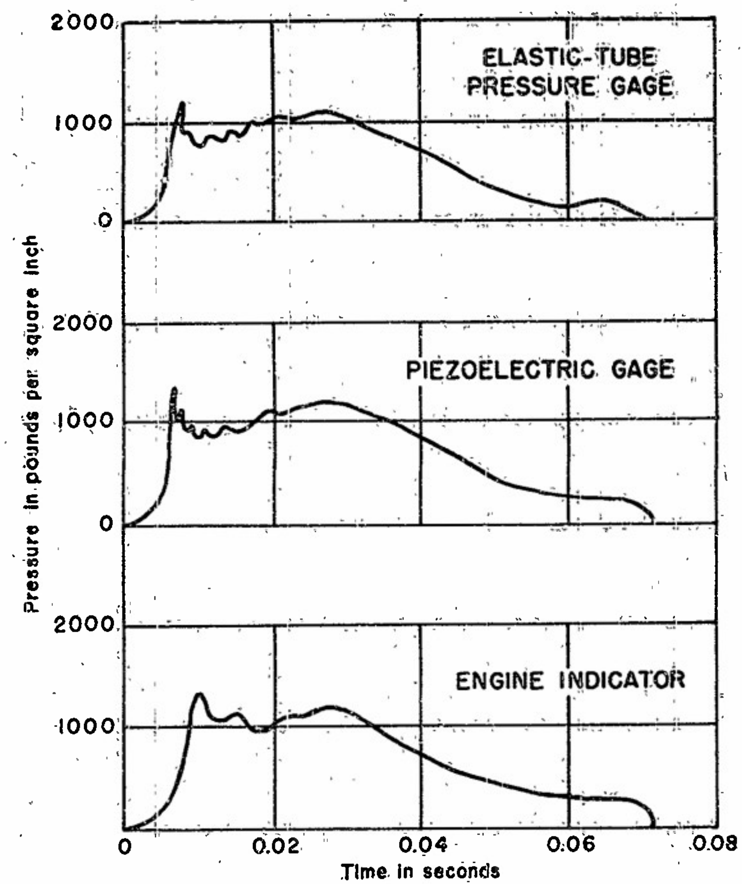

Figure 17 - Comparison of Pressure-Time Relationships Recorded with Different Gages During a Stroke of a Hydraulic Buffer

a bell were found to be 5100, 4000, and 5700 cycles per second respectively. Excitation could be produced only by external blows, and natural frequencies have never been observed during a test. Requirements for high natural frequency have been met.

CONCLUSIONS

The TMB Elastic-Tube Pressure Gage has been found to possess all the desired operating characteristics. It has proved accurate and durable, and, as a laboratory instrument, compares more than favorably with other types now on the market. Its use in the field of control instruments has not been explored, but the instrument appears suitable for such applications.

APPENDIX 1

DESIGN FACTORS WHICH INFLUENCE GAGE CHARACTERISTICS

Several brief comments are given here which pertain to the influence on pressure-gage characteristics of various design parameters. These relationships were determined mostly from experimental observations and may be considered as applying in the broad sense to the design of any similar type of measuring device which employs electrical elements of strain-sensitive wire.

SENSITIVITY

The sensitivity of the elastic-tube pressure gage earlier defined as the circumferential strain per unit pressure is a function of the thickness, diameter, and end restraint of the tube, of the modulus of elasticity of the material of construction, and of the position, resistance, type, and arrangement of the strain-wire elements; these parameters are discussed in the following.

The geometry of the mechanical components inevitably involves the dilemma that the characteristics of high natural frequency and high sensitivity can not be obtained simultaneously. If the natural frequency of the gage is at least twice that of the dynamic phenomena being studied, no attenuation of response should occur; this design criterion must always be considered first.

The natural frequencies of vibration of the pressure gage, which may be excited by sharp pressure pulses or external stimuli, may be divided into two groups - those which accompany organ-pipe reverberation within the tube and those which accompany elastic deformation of the tube vibrating as a bell. With the acoustical reverberations, natural frequency may be calculated according to elementary physical laws which indicate that the frequency depends largely on the length of the tube and the density of the fluid. Experimentally determined frequencies are given on Pages 27 and 29. The elastic action may consist of either longitudinal deformation or circumferential breathing of the tube, and frequencies of vibration in both modes are much higher than those of an air-filled organ-pipe. Elastic action as a cantilever is a low-frequency phenomena, but the instrument shows no response to this type of elastic behavior.

The circumferential strain e developed in the tube is related to the diameter d and the thickness t by the expression

$$e = \phi\left(\frac{d}{t}\right) \cdot kp$$

where p is applied pressure and k is a constant. Thus maximum instrument sensitivity may be obtained after considerations of natural frequency through the use of large diameters and small thicknesses. Ultimately, the difficulties in manufacture and liability to damage and corrosion place a lower limit on thickness, whereas convenience in gage handling and installation place an upper limit on diameter.

To ensure linearity of response, the maximum value of the principal stress should be limited to a value below the proportional limit. Here, the proportional limit is the maximum stress at which the load-strain relationships are linear. The electrical output of the pressure gage in strain units, e, varies directly with the pressure-induced principal stress, and inversely with the modulus of elasticity E. Thus to obtain maximum sensitivity, while neglecting momentarily other design factors, the material which comprises the tube should have its ratio of proportional limit to modulus of elasticity as great as possible. This ratio for various possible gage materials is given in the following list.

Steel	
Medium	- 0.0012
STS	- 0.0022
Tool	- 0.0053
Aluminum	
61ST	- 0.0035
75ST	- 0.0013
Brass	- 0.0012
Cu - 70 per cent	
Zn - 30 per cent	
Bronze	- 0.0013
Cu - 90 per cent	
Sn - 10 per cent	
Lucite	- 0.007
Cellulose Acetate	- 0.007
Gold	- 0.0019
Cu - 6.3 per cent	
Ag - 2.1 per cent	

Inasmuch as the pressure-produced strain output is an inverse function of the modulus, materials with low moduli are thus to be favored in these instruments; these materials, such as lucite and aluminum, unfortunately also have undesirable properties of creep, hysteresis, and low endurance limits. Whereas aluminum has been tested in some experimental instruments because it low modulus furnished one means of obtaining the desired sensitivity, alloy steels of higher moduli demonstrate the better characteristics of linearity and stability. The ideal material of construction is yet to be found.*

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* It is to be noted that to achieve maximum sensitivity, the strains developed at rated pressure are close to the proportional limit of the material. The absence of a large factor of safety thus requires care in the choice of instrument for a particular application so as to avoid possible overloading.

The factor of end restraint of the tube is present when the tube is so short that it is limited in its elastic distortion by ends which are comparatively rigid. Such action probably occurs to some slight extent in these instruments, but the short length required for high natural frequency is more important. Effects of end restraint are a minimum at the longitudinal center of the tube so that circumferential strains developed there by internal pressure should be a maximum; consequently, the strain elements are mounted at that point. Because of the sharp variation in stress along the tube, hand-wound gages that have the strain wire concentrated in a small area are productive of greater electrical output than the larger commercial gages.

The electrical output of the instrument, when used in a bridge circuit, may be increased with the use of higher-voltage power supplies. However, because of limitations on current flowing through the strain gages, the resistance of the gages should be greater. Sensitivity, in effect, is a direct function of the resistance.

Increase in electrical output could also be obtained through the use of two active gages electrically connected in a bridge circuit so that the strains would be numerically additive. Lack of space on the tube has thus far prohibited this arrangement, but it has several features to recommend its use in the future.

It has been found that regardless of the type of arrangement of strain elements, the output of a single strain gage is limited to 2500 microinches per inch, since higher strains have been accompanied by zero shift, creep, and hysteresis of magnitudes greater than desired in a precision measuring instrument. The cause of this limitation on sensitivity has not been fully determined and is subject to further study.

LINEARITY OF RESPONSE AND STABILITY OF CALIBRATION

The characteristics of linearity and stability have been observed to depend on the type of material employed in the elastic tube and on its history of loading; these operating characteristics further depend upon the magnitude of elastic deformations under load, on the type of strain gages employed, and on the skill exerted in their application.

If materials known to have a linear stress-strain relationship are employed in the manufacture of the instrument, it is necessary only that the loading be restricted to the range in which a linear response is observed. As mentioned earlier, this condition limits the magnitude of elastic deformations and is determined experimentally. With some severely overloaded specimens, however, linearity of response can never be achieved, whereas with most, slight controlled pre-loading improves performance.

With the characteristics of stability and linearity of response, as with sensitivity, hand-wound strain gages are preferred to the commercial ones. However, skill in gage application is particularly important to obtain acceptable results. It is necessary that the bond between the strain gage and surface be bubble-free, and that the gage not be damaged, even superficially, during installation. Generally, the routine checks of gage and ground resistance are insufficient to determine if the strain gages are properly installed. Occasionally a poor gage may be detected if its zero-stress resistance varies by more than the tolerance specified by the manufacturer, but only the calibration itself can be relied upon to detect unsatisfactory operation of the gages.

TEMPERATURE COMPENSATION

The efficacy of temperature compensation would appear assured if the pairs of strain gages are mounted sufficiently close together to be subject to identical temperature variations. It has been observed, however, that other factors may interfere with this condition. It has been determined that the coefficient of expansion in a material sometimes depends on the direction of rolling, and that the coefficients may differ throughout the specimen. Also, in a complex instrument that involves sharp variations in cross section, temperature-produced dimensional changes are not uniform, nor is the temperature distribution itself uniform. Consequently, proper choice of the location of gages for effective temperature compensation is important in the design, and the determination of such locations is purely an empirical procedure. In any case, the mechanical elements on which the active and the compensating gages are mounted should be identical in size and shape.

It is well known that the gage factors of commercial strain gages may vary plus or minus two per cent of an average value specified by the manufacturer. This variation results in different sensitivities in pressure gages that are otherwise identical; it has no effect, however, on linearity or stability. Nevertheless, these variations in gage factor are important in obtaining full temperature compensation, for a maximum variation in the two strain gages may result in such poor compensation as to warrant rejection. Again the choice of strain gages is entirely a matter of trial and error. The only possible precaution lies in selecting pairs of gages from the same package in hopes that they may be identical in gage factor. These difficulties are not often experienced with the hand-wound elements.

APPENDIX 2

DESIGNATIONS FOR ELASTIC-TUBE PRESSURE GAGES

All TMB Elastic-Tube Pressure Gages are designated by a serial number whose parts have the following significance.

First letter - Type of construction and capacity of instrument as given in Table 1.

TABLE 1

Dimensions and Designations of Elastic-Tube Pressure Gages

Type	Test Pressure psi	Mechanical Design	Dimensions of Tube, inches	
			Outside Diameter	Inside Diameter
D	8000	Original	0.478	0.438
E	5000	Original	0.466	0.438
F	20,000	Original	0.466	0.345
G	1000	Original	0.747	0.718
H	25,000	Revised	0.466	0.345
J	5000	Revised	0.466	0.438

Second letter* - Resistance and type of strain gage. The letters have the following significance:

Letter	Meaning
None	Type A-7, 120-ohm metalectric gage
A	Type A-14, 500-ohm metalectric gage
B	120-ohm gage, hand wound with 1.5-mil wire
C	500-ohm gage, hand wound with 1.5-mil wire

* An "affix" "X" after the first two letters of an instrument designation indicates that the shield of original design has had the Amphenol type plug replaced by a Cannon type plug.

Number - Serial number of the particular type of instrument.

Last letter - Number of different strain gages that have been installed successively on that particular mechanical component of the instrument.

Letter	Meaning
A	Second installation
B	Third installation

Thus the gage labeled ECX3B is a Type E gage of original design with a capacity of 5000 pounds per square inch. It is hand-wound with 500-ohm strain gages and is provided with a Cannon type plug. It is the third of the EC group of instruments and has been successively equipped with three identical strain gages.

APPENDIX 3

METHOD OF APPLYING NEOPRENE WATERPROOFING TO STRAIN GAGES

It is necessary to thoroughly waterproof strain gages after their installation, inasmuch as the cement for mounting gages is hygroscopic. The absorption of moisture by the cement does not appreciably affect the sensitivity, but it destroys the stability of the gage and reduces its service life.

Compounds such as beeswax or ceresin wax were first employed for waterproofing, but their brittleness at low temperatures was found to be objectionable. Bitumastics such as Ozite B have been superior in that respect, but are dissolved by hydraulic fluids and oils to which strain gages may be exposed. Neoprene has since been found to be the most effective waterproofing compound, and comprehensive tests with it have shown that it has no deleterious effect on the accuracy of strain measurement. The process for applying neoprene, which is commercially available from Gates Engineering Company, New Castle, Delaware, is given in the following:

1. Apply one coat of primer, with a brush or a spray gun, and allow it to dry one-half hour.

2. Mix the accelerating fluid and brushing cement in the proportions of one to four and apply a coating that will be approximately 1/64 inch thick.

3. Add as many additional coats as are required to build up the desired thickness of waterproofing; and allow one hour drying time between application of each coat.

4. Air-dry the completed coating for 24 hours.

5. Cure the coating at 140 degrees fahrenheit for a period of 12 to 18 hours. If this temperature is exceeded, the strain gages may be permanently damaged, and the paper charred.

REFERENCES

(1) "An Elastic-Tube Gage for Measuring Static and Dynamic Pressures," by E. Wenk, Jr., TMB Memo 3 for file S87-6, September 1946.

(2) "An Elastic-Tube Gage for Measuring Static and Dynamic Pressures," by E. Wenk, Jr., Technical Paper presented at annual meeting of Instrument Society of America at Pittsburgh, September 1946.

(3) "A Carrier-Type Strain Indicator," by George W. Cook, TMB Report 565, November 1946.

PRNC-5651-5-11-48-200